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To: D. Mills
Director of Research

TRIP REPORT
SECOND WORKSHOP ON MILITARY ROBOTIC APPLICATIONS

S.B. Nickerson

A paper was presented at the Second Workshop on Military Robotic Applications in Kingston, Ontario, August 8-11, 1989. The paper titled "Active Vision Navigation of a Mobile Robot in a Known Environment", [illegible] overview of a feasibility study report that has recently been submitted to PRECARN Associates Inc.

The second Workshop on Military Robotic Applications, August 8-11, 1989 at Kingston, Ontario, was sponsored by the Royal Military College (RMC) and the Defence and Civil Institute of Environmental Medicine (DCIEM) and took place on the campus of RMC.

There were 61 papers in 11 sessions:

1. Sensors and Sensing.
2. Navigation and Telerobotics.
3. Army Robotics and Requirements.
4. Overview.
5. Space Robotics.
6. Power Sources and Actuators.
7. RPV (Remotely Piloted Vehicles).
8. Underwater Mines.
9. Robot Control.
10. AI-Graphics.
11. Maintenance/Servicing/Simulations.

A paper was presented in the second session (Navigation and Telerobotics) which presented a non-technical overview of work carried out during a feasibility study for PRECARN Associates Inc. The paper is attached as Appendix 1 and a copy of the overheads used for the talk is Appendix 2.

There was one other paper on a proposed PRECARN project ("Telerobotic Control of Heavy Hydraulic Equipment" given by G. Immega of MacDonald Detweiller & Associates) and an overview paper on PRECARN itself, given by J.C. Gavrel, Director of Research Programs at PRECARN.

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APPENDIX 1

ACTIVE VISION NAVIGATION OF A MOBILE ROBOT IN A KNOWN ENVIRONMENT*

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Abstract

This paper describes a research project developed during a feasibility study prepared for PRECARN Associates Inc. The proposed project is now (August, 1989) being reviewed. The organizations involved in the feasibility study are Ontario Hydro, the University of Toronto, York University, Atomic Energy of Canada Ltd. (AECL) and the National Research Council (NRC). The main goal of the proposed project is to build a mobile robot that can navigate in a known indoor environment using vision as its main sensor and internal models as its world reference. A second goal is to explore the technology in such a way as to best illustrate its usefulness and commercial potential. The theory will focus on the development and testing of computer vision algorithms as aids for robot navigation. Two robots will be built: ARK-1 (Autonomous Robot for a Known Environment) at the University of Toronto; and ARK-2 at AECL in Mississauga. ARK-1 will be tethered and will be used to test the vision algorithms. ARK-2 will be untethered, will use other sensors in addition to vision, will have a real-time operating system and will operate in an industrial environment. The platforms for both ARK-1 and ARK-2 will be the same as that of a robot already being developed at NRC for medical applications. Ontario Hydro is a potential end user of this technology, AECL will commercialize both the mobile robot technology and the computer vision technology, NRC will be able to enhance their own program and the Universities will have an opportunity to test their vision theories with a mobile robot. If funded, the project will last four years and involve an estimated 89 person-years of effort.

* This work is supported in part by PRECARN Associates Inc. and the Industrial Research Assistance Program of NRC.

Introduction

This research project was developed during a feasibility study prepared for PRECARN Associates Inc. The main objective of the project will be to build an autonomous robot that can navigate in an indoor environment using a vision system as its main sensor and internal maps as its world reference. Other objectives include the exploration of the limits of vision technologies and the promotion of the research and development of mobile robotics in Canadian industries. There will be three groups of participants in the project: industrial participants (Ontario Hydro Research Division and AECL Advanced Systems), university participants (the Departments of Computer Science at the University of Toronto and York University) and a government participant (the Electrical Engineering Division at the National Research Council of Canada.) The project will concentrate its main efforts on vision related research, and in particular, on the development and testing of computer vision algorithms as aids to navigation. The project is presently being reviewed by PRECARN.

The project is divided into three programs centered around each group of participants. The university participants will be responsible for building a tethered robot, ARK-1 (Autonomous Robot for a Known environment), and for developing and testing the vision-based navigation algorithms on the robot. It is expected that many graduate students will be involved in the project through their theses work. The industrial participants will be responsible for building an untethered robot, ARK-2, to convert the developed software into a real-time environment, extend the software capability to allow the operation of the robot in an industrial environment and investigate the use of additional sensors. NRC has already built a robot and has an independent ongoing mobile robot program. NRC will continue to

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Royal Military College of Canada, Kingston, Ontario

manage their own program and will provide the rest of the project with the technology that they have already developed and will develop during the project. In return they will receive any technology developed by the rest of the participants.

Ontario Hydro is motivated by the potential applications of mobile robots in the radioactive areas of its nuclear power plants, and in particular, by their use for inspections and collection of environmental samples. AECL Advanced Systems is also interested in these applications, but, in addition, it is interested in the commercial possibilities of robotic and vision technologies. NRC is motivated by the opportunity to exchange their technology for that developed by the rest of the participants. The universities are interested in testing the theoretical ideas they have developed in a real system.

Technical Overview

As already mentioned, the technical objective of the project is to build an autonomous robot that can navigate in an indoor environment using vision aided by internal maps. The focus of the research will be on identifying the limitations of the vision system and on equipping the robot with spatial reasoning abilities to rectify these imperfections. To minimize the amount of hardware development, the platforms for both ARK-1 and ARK-2 will be the same as that of the robot that has been developed at NRC for medical applications. This will allow the use of the NRC control programs by the rest of the project.

The project will be divided into three programs, each under the responsibility of one of the participating groups. These programs are described below. The principal theoretical element of the project will be vision, which is the main expertise of the university faculty involved in the project. Other theoretical elements that will be investigated are uncertainty and sensor fusion (ie., how to deal with errors in sensor data and how to deal with conflicting data from different sensors).

The vision theory being applied to mobile robotics is lagging behind the current theoretical developments in the computer vision literature. Therefore, there is an opportunity to adapt new computer vision developments to mobile robots. The vision research will focus on extending the existing "static" algorithms to "active" sensor algorithms. The active algorithms will be part of a closed loop system that will actively change the parameters of the imaging system (such as focal length) to address areas of ambiguity of the output of the visual processing. Two important components of this research will be: (i) to make the vision algorithms aware of their limitations (including the ability to identify areas where the results of the processing are not qualitatively reliable); and (ii) to make the vision algorithms able to plan new camera parameters that will help to reduce the qualitative uncertainty in the results of the processing. In the above the term "qualitative" is interpreted to mean sufficient for robot navigation.

Since the project will be concerned only with indoor navigation, the robot will be able to use internal models and maps to assist in long distance planning. These maps will have the level of detail of floor plans supplemented by additional data about the environment such as ceiling height and door height. There will be many obstacles and features in the environment that will not be in the data base of the robot, so that the robot will have to identify these with its sensors. Feedback from the vision and other short range sensor systems will be used for obstacle avoidance.

Other robotic projects have appeared in the literature that, similar to ARK, are aimed at an indoor environment, have cameras as sensors and use a priori maps. These include: the HERMIES (Hostile Environment Robotic Machine Intelligence Experiment Series) projects and the DOE/NE University program in Robotics for Advanced Nuclear Reactors at Oak Ridge National Laboratory (ORNL) [3,7,13,14 and 20]; the HILARE project at the Laboratoire d'Automatique et d'Analyse des Systems - Centre National de la Recherche Scientifique (LAAS-CNRS), Toulouse, France [11 and 12]; LURCH at Grenoble [4,5 and 6]; the INRIA project [1 and 9]; the University of Amsterdam project [19]; the CMU Rovers projects [8, 15 and 16]; the MIT robots [10]; the Oxford project [2]; and the Osaka project [17, 18 and 21]. The projects that are more closely related to the ARK project are the ORNL HERMIES and the Oxford projects. The robots of these two projects have a considerable amount of on-board computing, use or will use vision for navigation, will have real-time operation, will operate in an industrial environment, and have definite goals and applications. In addition, these projects have the critical amount of resources necessary to carry out their work without discontinuities. All of the other projects lack one or more of the above elements. The ORNL HERMIES project is aimed at a nuclear environment and the Oxford robot will operate in a warehouse environment. In contrast, the ARK project will develop software aimed at a large industrial plant floor environment. Another difference between ARK and the ORNL and Oxford projects is the project leadership. ORNL is government led with university and industry participation and the Oxford project is university led with industry participation. ARK is led by industry with university and government participation. This difference means that those involved with ARK will be able to move quickly to commercialization when the technology is mature enough.

Program Elements

University Program

The main component of the university program is an in-depth examination of existing active vision algorithms with the intent of using selected algorithms as the basis of the sensory component of the robotic system. In particular, the use of spatio-temporal filtering as the first level of visual processing, and the ability to construct stereo and optical flow algorithms that operate directly on the output of these filters will be examined in detail. As the algo-

rithms are successfully developed, they will be implemented on ARK-1.

Four separate research topics will be investigated during the first two years in order to determine the best components for ARK-1. During the last two years there will be considerable interaction with the Industrial program. The following is a description of the five elements of the University Program:

1. Depth Computation. This will concentrate on the use of active vision to provide depth information. The techniques to be investigated are: verging stereo through an active sensor system, visual tracking through an active sensor system, optical flow using spatio-temporal filters, and occluding boundary detection from stereo and optical flow. Other ranging techniques such as sonar, laser range finder, etc., will be used to assist the vision system, if needed. Existing technology and algorithms will be employed as much as possible.

2. Low Level Motor Abilities. The goal of this program element is to demonstrate hallway traversal, corridor junction navigation and navigation in an environment where dynamic objects exist.

3. Recognition. This element will deal with the recognition of objects in the environment with prestored representations of those objects in the robot's memory.

4. World Model for Spatial Reasoning. This element will develop an internal representation of the environment for the robot, including a formal specification of the model and mechanisms to access the model.

5. Interaction with the Industrial Program. This will consist of work carried out by students either directly for ARK-2 or as a continuation of work started during the first two years with ARK-1.

The first four program elements can proceed independently, and it is not until the later half of the second year that all the initial projects must be completed. Several milestones have have been identified (see Figure 1, which also shows the milestones for the Industry Program).

The platform for ARK-1 will be based on the 3-wheeled Cybermation K2A platform, the same platform used in the NRC Program. Other equipment includes three high resolution cameras with motorized lenses and frame grabbers, a pan and tilt assembly, ultrasonic sensors and an emergency stop switch. The robot will function primarily in laboratory conditions and it is expected that the integration effort spent in terms of electrical and mechanical interfacing will be only sufficient to allow ARK-1 to function as a developmental prototype. The communications between the computer systems and the Cybermation platform will be through a wire tether.

Industrial Program

The main objectives of the industrial program are to build an untethered robot, ARK-2, to convert the developed software for ARK-1 into a real-time environment, to extend the software capability to allow the operation of the robot in an industrial environment and to investigate the use of additional sensors. The elements of the program are listed below. Some of these elements are independent of each other, while others are quite interrelated. Figure 1 shows the milestones.

1. ARK-1 Development. During the development of ARK-1, there will be considerable interaction with the University participants and with NRC. This will include visits to NRC to study their robot, building ARK-1, provision of uncertainty theory for ARK-1, and participation in the development of ARK-1 software.

2. ARK-2 Design, Component Acquisition, Construction and Hardware Testing. Design of ARK-2 will start six months into the project after the hardware tasks of ARK-1 are completed. By the end of the second year, it is expected that the construction of ARK-2 will be completed, including the selection of all sensors. The inclusion of other than vision sensors will depend on the performance of the vision and sonar systems.

3. Vehicle Control. The low level control will be based mainly on the work that NRC has already done, although some adaptation may be required.

4. Computer Program Architecture. This element will consist of the overall design of the software and will be based on existing techniques.

5. Navigation. The purpose of this element is to give ARK-2 the ability to move from its present position to any other within a complicated environment using its sensor system and internal maps. A secondary goal is to make the robot able to produce a contour map (within an arbitrary area on its internal map) of a quantity, such as noise levels, that can be measured with its non-navigation sensors. Two different environments will be used to test the navigation capability of ARK-1: an office environment and an industrial plant floor environment.

6. Uncertainty. Uncertainty will permeate every aspect of the software from representation to sensor fusion. This element will be a continuation of the uncertainty work done for ARK-1 under the ARK-1 Development program element.

7. Spatial Reasoning. This element will be based on the work done under the University Program. The previous work will be adapted to the two new environments at the AECL site.

8. Maps. Internal maps will be used for both planning (is ARK-1 to turn left or right?) and navigation (matching the internal map to the camera data to determine ARK-2's position). Maps will be developed for both the office and the industrial environment at AECL.

9. Vehicle Model. Under this program element, a computer model of the vehicle and its sensors will be developed. This is necessary for correct interpretation of the sensor data.

10. Planning. This element is divided into planning based on sensor data (obstacle avoidance) and on map data (how to chart a route from one side of the building to the other).

11. Code Transfer to NRC. This element will cover the effort to transfer the ARK-2 code to NRC for use with their robot.

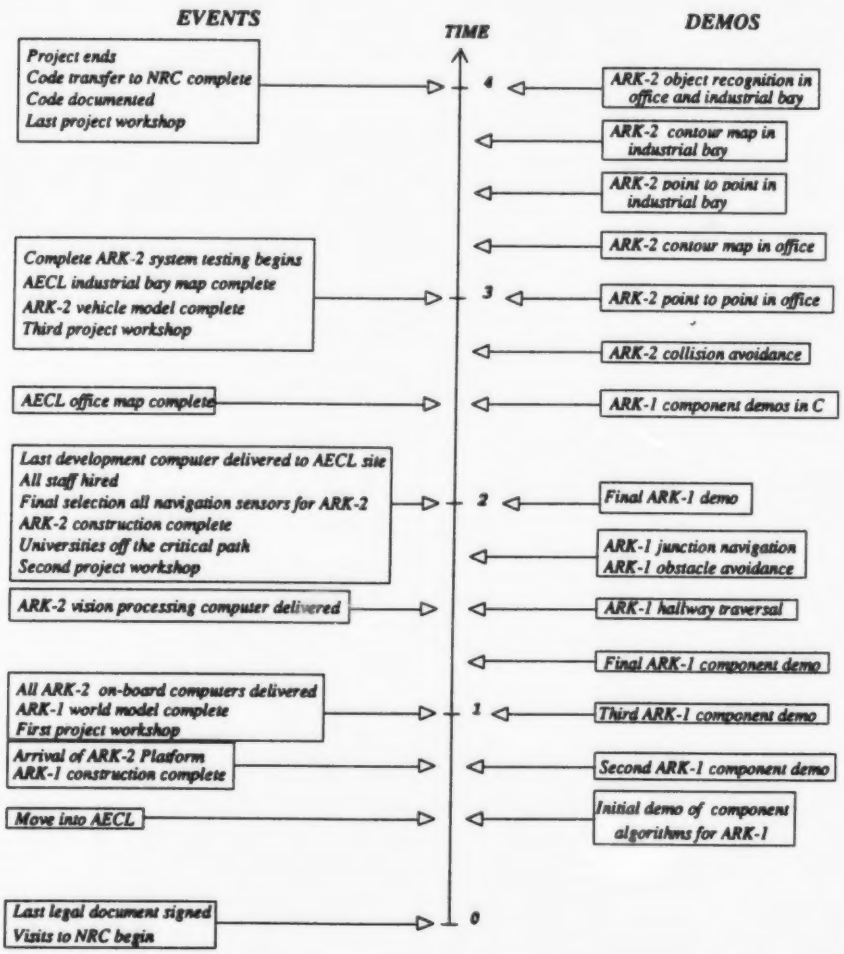

FIGURE 1: Industry and University Program Milestones. Point to point means that ARK-2 can move autonomously between two arbitrary points using its sensors and internal maps.

12. Software Integration and ARK-2 Testing. Taking place in the last year, this will be the most important element since it involves the integration and testing of all the hardware and software elements that make up ARK-2.

The platform for ARK-2 will also be the Cybermation K2A. Other equipment is similar to ARK-1's with the addition of a communications system (ARK-2 will not have a tether), a number of on-board MC68030 modules, more computing power, and additional sensors.

NRC Program

The NRC Program is concerned with the development of mobile robot technology for health care applications. It has two major components: the investigation and specification of appropriate applications of mobile robots in the health care field and the development of generic technology required to properly control a robot.

The health care application component consists of the following elements.

1. Environmental Measurements. To assess the requirements and physical limitations of the vehicle, room, corridor and door sizes are being measured and analyzed. In addition, the type and speed of the movements of objects in a hospital environment are being analyzed. Noise and light levels as well as traffic flow rates have been measured and a number of potential hazards in the environment. have been itemized

2. Characterization of Patients and Patient Records. This analysis of representative patients and records is important in determining the number of potential users for patient transport vehicles.

3. Analysis of Other Robot Devices. An assessment group of health care professionals and patients was formed to analyze potential robot application ideas for the device.

The generic technology component consists of the following elements.

1. Control Methodologies. A hierarchical program control architecture has been developed. The lowest levels (vehicle motor control) and the second level (vehicle trajectories) have thus far been implemented.

2. Computer Architectures. A flexible real-time architecture, based on NRC's real-time operating system, Harmony, for on-board control has been developed.

3. Range Sensors. This program element consists of the development of a ring of 24 ultrasound transducers, an active IR laser "slit scanner" device, and a stereo vision system.

4. Drive Control. A trajectory generator has been developed that provides smooth and predictable motion between specified points in 2-D space.

5. Navigation. An investigation has been started into data representation methods for the generation of local maps based on sensor views.

The NRC robot has a Cybermation K2A platform with a ring of 24 ultrasound transducers and three on-board 68020 modules.

Conclusions

The proposed research project to build an autonomous robot using vision for navigation will make a significant contribution in several areas. In particular: (i) it will contribute to the vision and mobile robotics state-of-the art; (ii) it will lead to commercial activity in mobile robotics and computer vision; (iii) it will bring state-of-the-art vision theory into industry; and (iv) it will assist in the evaluation of the commercial potential of the results of other active vision projects carried out at the University of Toronto and York University. In addition, since the project is not aimed at a specific application, it will provide precompetitive research that could be used in several types of future robots. One of the major potential applications of the results of this research will be the construction of a robot for the inspection and sampling of the radioactive areas of Ontario Hydro's CANDU nuclear stations. Other possible applications would include: indoor patrol robots, inspections in large industrial facilities such as oil refineries, warehouse floor cleaning, hospital and in-home care for the sick, flexible manufacturing, and if we look ahead far enough into the future, personal robots.

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ACTIVE VISION NAVIGATION OF A MOBILE ROBOT IN A KNOWN ENVIRONMENT *

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A presentation at the
Second Workshop on Military Robotic Applications
Royal Military College of Canada
August 8 - 11, 1989
Kingston, Ontario

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TALK OUTLINE

- o Background
- o The proposed project
- o Economic impact
- o Summary

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BACKGROUND

- Feasibility study for PRECARN Associates Inc.
- Main result: definition of a research program in the use of active vision as an aid to the navigation of a mobile robot
- The proposed project is now being reviewed by PRECARN

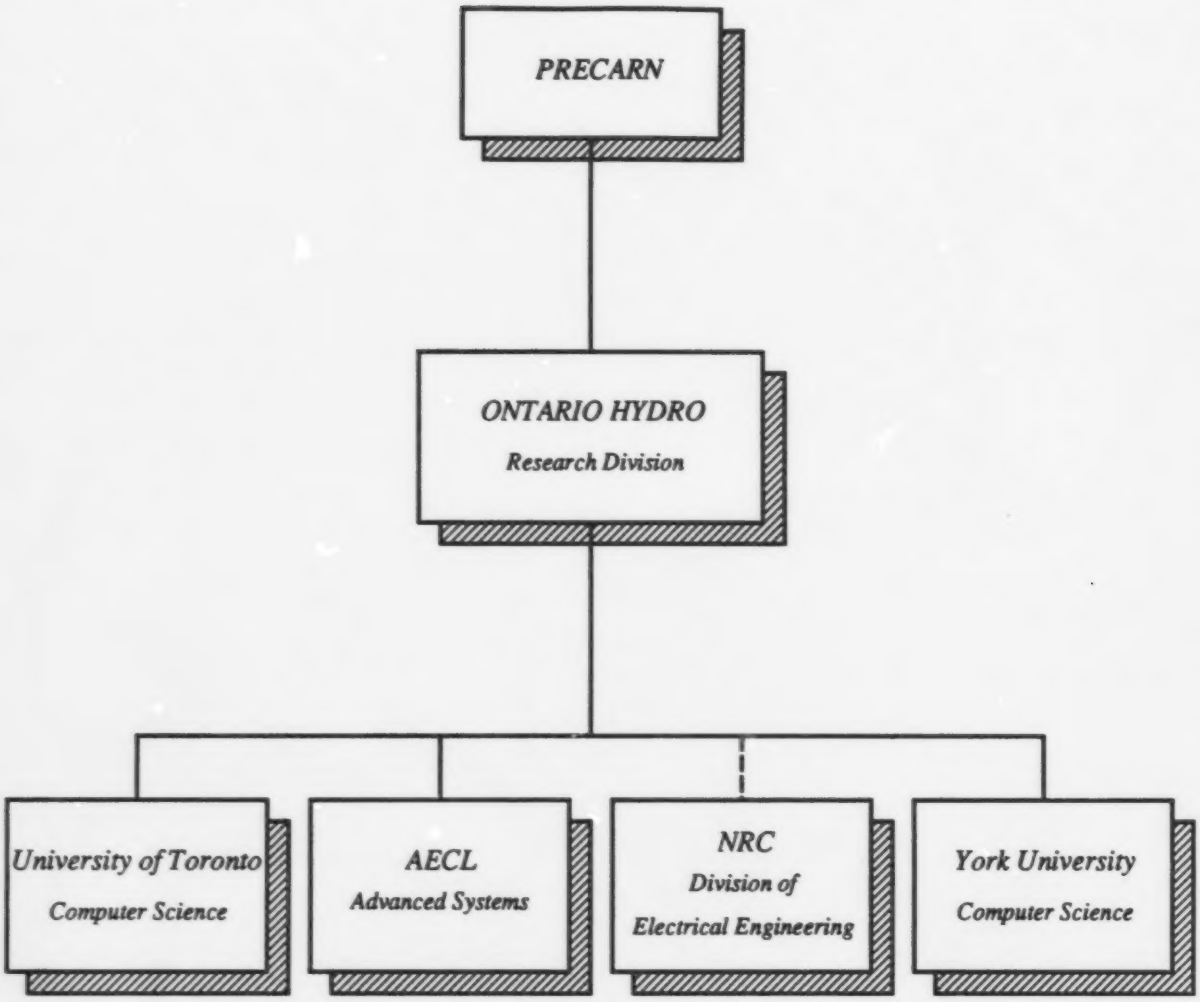

Figure 3.1: ***Relationships Between the Organizations Involved in the Project. Ontario Hydro is responsible for project management. A solid line represents a contractual relationship and the dashed line represents exchange of technology for scientific research purposes.***

PROJECT GOALS

- To build a mobile robot that will be able to navigate in a known indoor environment using internal maps and vision as its main sensor.

- To explore the limits of the technology in such a way as to best illustrate its usefulness and commercial potential.

- To ensure continuity of R&D in mobile robotics and computer vision after the PRECARN funding is complete, through commercialization or new research projects at the participant institutions or through activity at PRECARN member companies.

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PROJECT FOCUS

AREA TYPE		*KNOWLEDGE OF AREA* KNOWN	UNKNOWN
	STRUCTURED (INDOORS)	X	
	UNSTRUCTURED (OUTDOORS)		

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ACTIVE VISION

- Expertise rests with the university participants
- Active vision refers to a system that provides scene information by actively changing the geometry of, or moving, the optial system
- Research is aimed at making the vision algorithms part of a closed loop system that will actively change the camera parameters to address areas of ambiguity in scene information
- Examples of camera parameters are focal length and relative positions of the two cameras in a binocular system

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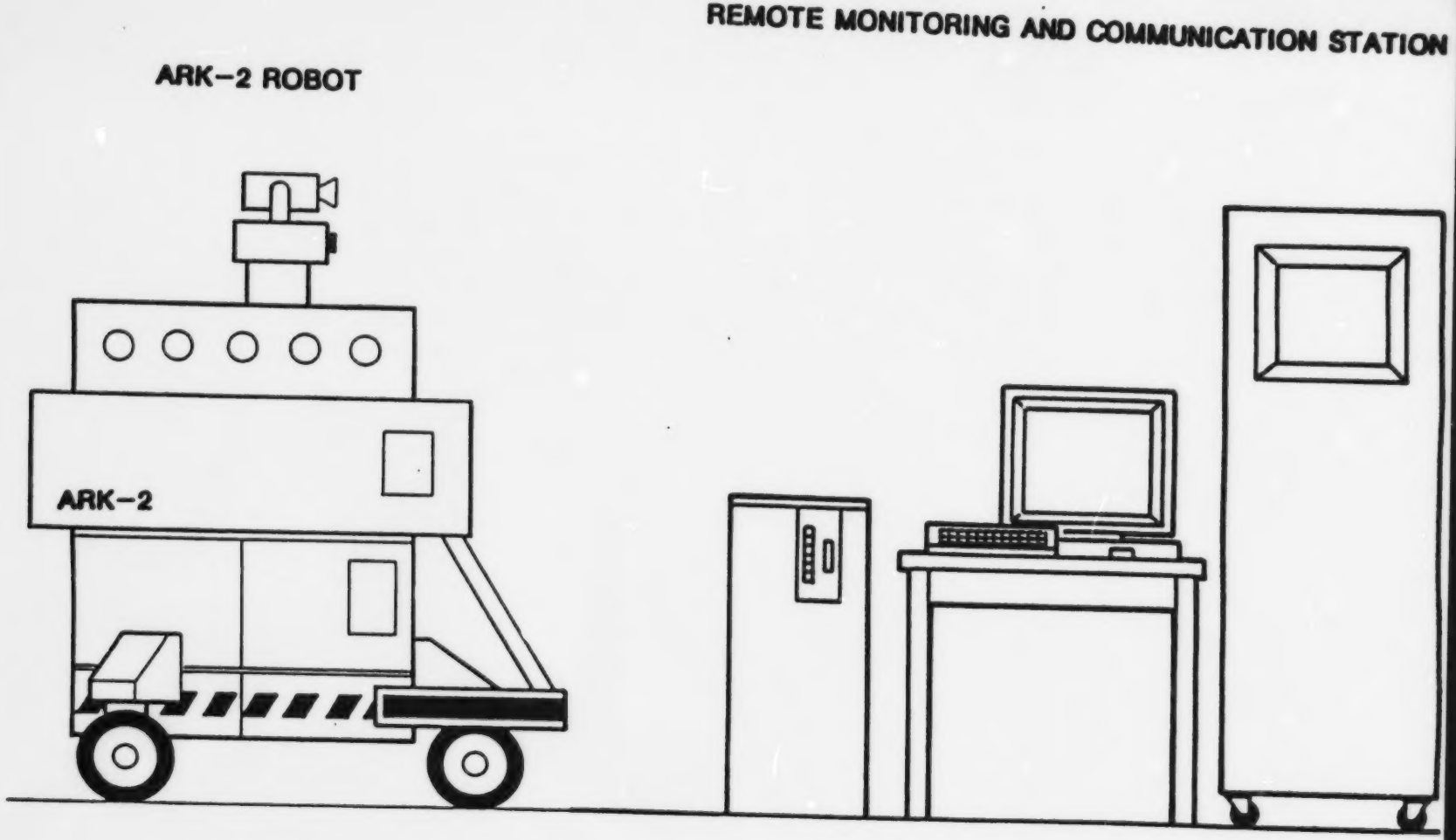

Figure A.4 ARK-2 Conceptual Sketch

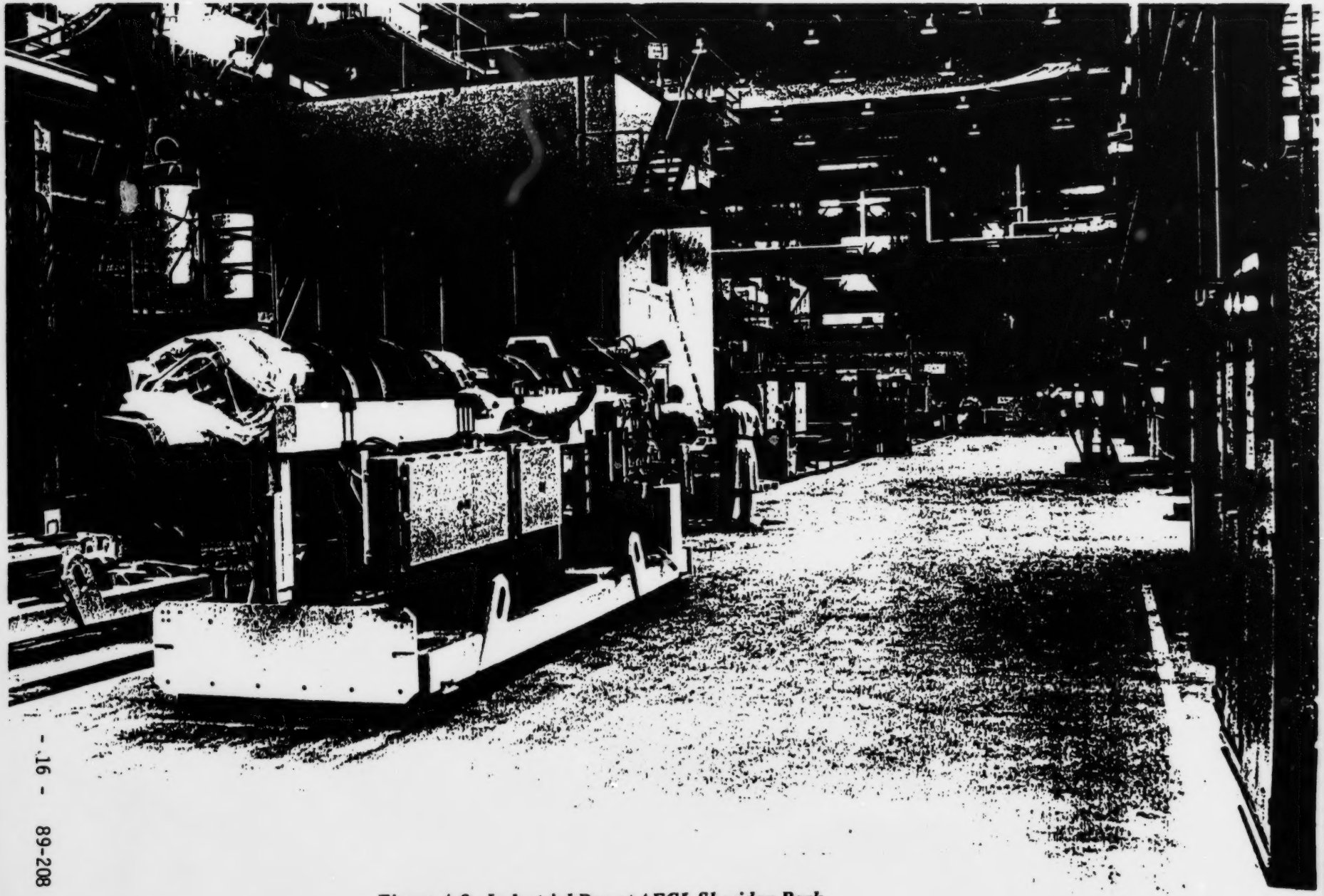

Figure A.9 Industrial Bay at AECL Sheridan Park

Figure A.7 Industrial Bay at AECL Sheridan Park

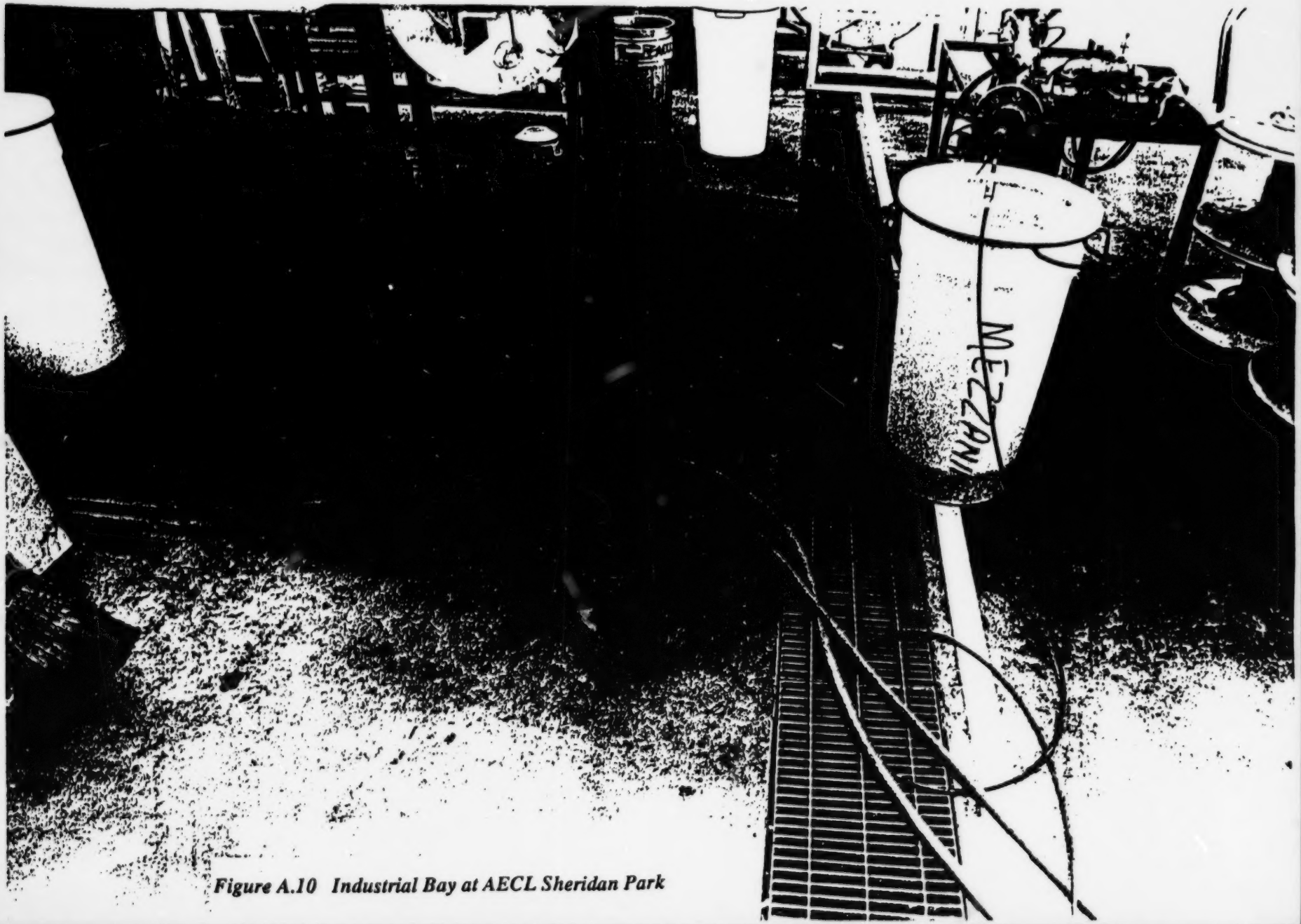

Figure A.10 Industrial Bay at AECL Sheridan Park

Comparison Between Project Robots

Feature \ Robot	NRC Robot	ARK-1	ARK-2
Home	NRC	U Toronto	AECL Miss.
Platform	Cybermation	Cybermation	Cybermation
Tether	Yes	Yes	No
Environment	Lab	Lab/office	Lab/office Industrial
Language	C	LISP	C
Real Time Operatiuon	Yes	No	Yes

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Comparison Between Project Robots

(continued)

Feature \ Robot	NRC Robot	ARK-1	ARK-2
Sensors For Navigation	Basic* Laser Slit (F)	Basic*	Basic* Laser Range Finder (U) Inclinometer (U) Microphone (U) Gyro-compass (U) Clock (U)
Application	Medical	Vision Testing	Industrial Environment

** The basic set of sensors is sonar, bumper, dead reckoning and one or more cameras. F means Future and U means Under consideration.*

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Table 4.1: The Market for Mobile Robots Using Vision for Navigation.

This table shows a qualitative picture of the market for mobile robots using vision for navigation, based on the opinions of the authors of this report. Many of the applications would require additional capabilities still in the research stage. Some examples are: an on-board vision guided manipulator, or the ability to recognize objects and things out of the ordinary. Economics aside, each of the applications in this table would benefit to some degree by the use of today's mobile robot technology and each would also benefit much more from the use of a vision-based navigation system. A range in the Complexity of Task column indicates that a range of tasks is anticipated (which can result in a range in price). A range in the other columns indicates uncertainty. Near term indicates 0 - 5 years after the end of the proposed research program; the rest of the quantifiers are only defined relative to each other.

APPLICATION	*RETAIL PRICE DOMAIN*	*WHEN ECONOMIC*	*MARKET SIZE*	*COMPLEXITY OF TASK*
Nuclear	High	Near	Small	Low-high
Medical	Low	Near-med.[1]	Med.	Low
Flexible Manufacturing	Low-Med.	Med.-long	Med.	Low-high
Patrol	Low-med.	Near	Med.	Low-med.
Warehouse	Med.	Near	Small-med.	Low
Fusion	High	Long[2]	Small	Low-high
Personal & Domestic	Very Low	Long	Huge	Med.-high

[1] Safety issues of dealing with incapacitated humans may delay some medical applications.
[2] Because fusion is long term.

Table 4.2: Forecast Market for Non-industrial Robots [MILLER 88b]

Below is the forecast US market for intelligent mobile robots in 1990, 1995 and 2000, based on a panel of 30 experts in the field. The units are millions of $US. Only those applicable to the ARK project are listed.

Application	*1990*	*1995*	*2000*
Nuclear	20	25	36
Hospital & Medical	10	50	120
Mail Delivery, Office Automation	10	30	40
Cargo Handling & Transportation	10	20	50
Indoor Surveillance	10	15	30
Handicap Assistance	7	20	40
Floor Cleaning	5	20	40
Personal & Domestic	5	15	50
Restaurants & Fast Food	5	10	40
Retail & Grocery Stores; Pharmacies	2	10	20
Total	84	215	466

SUMMARY

- A project in applied computer vision with mobile robotics as the application area
- Joint project of industry, government and university
- Status: a proposal to PRECARN
- Decision: this fall

ontario hydro research division